論文 A Restoring Force Model for Partially Prestressed Concrete Piers

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ABSTRACT: Since partially prestressed concrete has shown superior restoration characteristics, it was proposed to implement it in bridge piers to reduce residual displacements after earthquake excitations. Small-scaled pier specimens were previously tested using reversed cyclic loading tests. Based on test results, the characteristic behavior of such PRC piers is clarified. Additionally, a restoring force model is proposed. A comparison between results obtained using the proposed model and those from pseudo-dynamic tests is also conducted. A good agreement is obtained thus verifying the accuracy of the model for implementation in response analyses.

KEYWORDS: Earthquake resistant structures; bridge piers; prestressed concrete; restoring force model; pseudo-dynamic test; dynamic analysis.

1. INTRODUCTION

Residual displacement of bridge piers after earthquake excitations is shown to be an important damage index that might prohibit reusability of RC bridges. Partially prestressed concrete (hereafter PRC) has shown high restoration characteristics and small residual displacements after an earthquake excitation [1], [2], and [3]. Consequently, it was proposed to make use of PRC in bridge piers. Nevertheless, the resulted characteristic behavior is a function of the considered amount and arrangement of prestressing tendons (PC) employed in the pier. Different types of PRC piers were proposed [4], [5].

The usability of PRC piers depends mainly on accurate identification of their characteristic behavior during simulated earthquake excitations. Different restoring force models for PC members, to be implemented in response analyses, have been previously presented. In general, these models can result in good prediction of accumulated absorbed energy but they deficit accurate estimation of residual displacement after simulated earthquake excitation. Consequently, the objective of this study is to clearly identify the characteristic behavior of such PRC piers and to obtain a restoring force model that can accurately assist in predicting residual displacements.

Small-scaled PRC piers were previously tested using statically reversed cyclic loading tests [2], [6]. Based on test results, the characteristic behavior in terms of accumulated absorbed energy, residual displacement and equivalent damping factor are obtained. Also, a restoring force model that enables to capture these characteristics is proposed. Results of these characteristics obtained by the proposed model are compared with those obtained experimentally. Further verification of the proposed model for use in dynamic analyses is achieved through direct comparison between results obtained using it and those from pseudo-dynamic tests [1], [2]. The Hyogo-Ken Nanbu 1995 earthquake excitation (NS direction) was used. The comparison showed a good agreement for both hysteretic behavior and time histories. Since an accurate prediction of maximum displacement, residual displacement, response during the entire excitation and overall hysteretic behavior is achieved, the accuracy of the proposed model is verified for future employment in dynamic analyses.

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2. PRC PIER SPECIMEN VARIABLES

Results of seven specimens previously tested [1], [2], [6] under Prestressed Concrete Pier Research Project were used. Specimens have strength ratios, which are the ratio of shear capacities divided by flexural capacities of about 1.50 to ensure a final flexural failure. An axial stress level of 1 Mpa was imposed to specimens. Nominal strength concrete of 35 Mpa was used. One experimental variable was the mechanical prestressing ratio (λ), which is defined as contribution of PC tendons in overall capacity of cross section. Values of (λ) ranged from 0.00 for RC specimen (S-1) to 0.86 for PRC specimen (S-5). Another variable was the usage of ungrouted PC tendons (specimens S-4, S-4P). The last experimental variable was the testing type. Five specimens were tested under statically reversed cyclic loading. The objective was to identify the inelastic behavior characteristics and to obtain an accurate restoring force model for PRC piers. The last two specimens were tested using pseudo-dynamic testing technique [7]. Modified excitations of the Hyogo-Ken Nanbu 1995 (NS-direction) earthquake were used. Maximum accelerations for specimens (S-1P) and (S-4P) were 563 gal and 474 gal respectively. An elastic natural period, of specimens (S-1P) and (S-4P), is 0.3 sec. Details of specimens are shown in Table 1 while whole description and instrumentation can be found elsewhere [1], [2], and [6].

Table 1: Details of specimens

Spec. No.	**Reinforcing bars**		**Prestressing tendons**		**Shear reinforcement**		**Mechanical Prestressing Ratio (λ)**	**Test Type**
	Rein.	**(As/bd) %**	**Tendons**	**(Aps/bd) %**	**Hoops**	**(Ash/bs) %**		
S-1	32D13	2.65	---------	---------	D6@3 cm	0.47	0.00	Cyclic
S-2	16D13	1.41	4 SWPR7B ϕ12.7	0.33	D6@3 cm	0.47	0.33	Cyclic
S-3	16D10	0.79	8 SWPR7B ϕ12.7	0.63	D6@3 cm	0.47	0.64	Cyclic
S-4	16D10	0.79	8 SWPR7B ϕ12.7	0.63	D6@3 cm	0.47	0.64	Cyclic
S-5	8D10	0.42	8 SWPR19 ϕ17.8	1.32	D6@3 cm	0.47	0.86	Cyclic
S-1P	32D13	2.65	---------	---------	D6@3 cm	0.47	0.00	PSD
S-4P	16D10	0.79	8 SWPR7B ϕ12.7	0.63	D6@3 cm	0.47	0.64	PSD

3. EXISTING RESTORING FORCE MODELS FOR PRC PIERS

Thompson and Park [8] developed an idealization for moment-curvature characteristics of PRC members under reversed cyclic loading by combining responses of PC modified idealization, presented by Blakelay, and Rambörg Osgood idealization. The model is quite useful since it can cover the whole range of concrete from fully PC members to RC members. It was reported by Nishiyama et al. [9] that the model has two defects. In large ductility ranges, the PC model shows more pinched hysteresis than the actual one. Also, flexural cracking can not be explicitly defined in the RC model. Another disadvantage is that when a section has small (λ), loops especially for small displacement amplitudes, will be based on Rambörg Osgood idealization. It is believed that Takeda's one [10] is a better idealization.

Nishiyama et al. [9] presented a modification for the model by Thompson and Park to overcome the difference in predicting the pinching hysteresis in large ductility ranges but this model could not overcome the other disadvantages.

Okada et al. [11] proposed a restoring force model with rather complicated equations for PC members. Okada et al. commented that the model could give good conformity with experimental results though some differences were observed in the residual displacement.

Okamoto and Kato model [12] is a perfect model for PC members after cracking and before yielding. When unloading commences after yielding, the model can not capture the exact behavior since it has one unloading stiffness that can not represent the actual unloading stiffness especially for members having high values of (λ). The model can efficiently estimate the accumulated absorbed energy while it deficit good prediction of the residual displacement. Fig. 1 shows a comparison between experimental and analytical results obtained for specimen (S-3).

Hosaka et al. [13] presented a restoring force model for PC girders. The model showed a relatively good accuracy for members having small and moderate ratios of (λ). It was reported by Zatar et al. [1] that it could not give accurate prediction of residual displacements for members having high values of (λ) especially if ungrouted tendons exist. Fig. 2 shows a comparison between experimental and analytical results for grouted specimen (S-3) having λ=0.637. Fig. 1 and Fig. 2 show lacking of accurate predictions of the residual displacements.

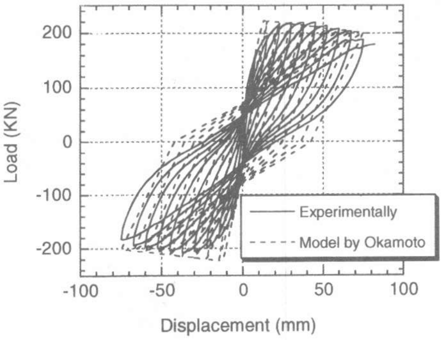

Fig. 1: Load-displacement curve for spec. (S-3)

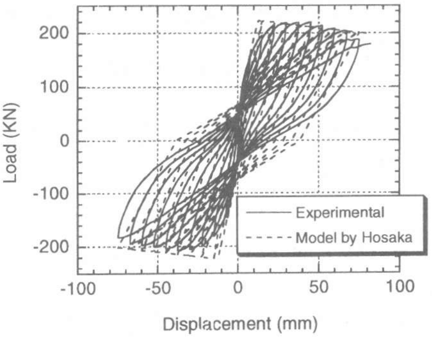

Fig. 2: Load-displacement curve for spec. (S-3)

4. A PROPOSED RESTORING FORCE MODEL FOR PRC PIERS

In order to accurately simulate cases of grouted or ungrouted PRC piers and to obtain a better estimation of residual displacements, a new restoring force model is proposed. The model can, almost, capture the exact behavior since it accounts for change in stiffness during unloading by considering two unloading stiffnesses. One of the advantages of the proposed model is that it can overcome the deficiency of not accounting for effect of amount and arrangement of PC tendons and non-prestressing reinforcement for cases of PC piers in the model by Hosaka et al. Since the model by Hosaka et al. [12] was mainly proposed for PC girders where PC tendons and reinforcing bars are to be arranged near the extreme fibers, assumption of yielding for PC tendons and reinforcing bars is used in the calculation of the index (λ). The proposed model can account for such shortcoming through the calculation of (λ) as a function of actual stress of each PC tendons and non-prestressing reinforcement as shown in eq. 1. Stress values are to be calculated based on having a concrete strain of 0.0035 (Fig. 3). The model has the same characteristics and basic rules of Takeda's model [10] except for having two unloading stiffnesses (named K_{r1}, K_{r2}) (Fig. 4). The proposed model can account for the change of absorbed energy at small displacement amplitudes. The proposed model can also account for cases of PC members having any value of (λ). The turning point (Tp) about which the second unloading stiffness commences is a function of the mechanical prestressing ratio (λ) of the member. Values of K_{r1} can be obtained from eq. 3 based on having a constant α=0.4. Values of K_{r2} can be obtained from eq. 4 based on parameter (β) which is a function of the mechanical prestressing ratio (λ). Based on experimental results of specimens shown in Table 1 and based on

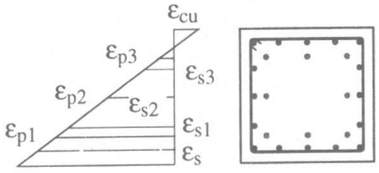

Fig. 3: Basis for consideration of PC tendons location in the model.

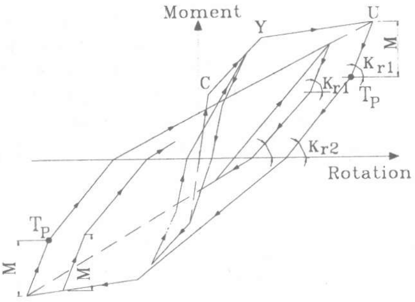

Fig. 4: Rules for the proposed model

other experiments, relationship between mechanical prestressing ratio (λ) and unloading parameter (β) is obtained (Fig. 5). It can be seen that the relationship between (λ) and (β) is linear until λ=0.4 after which (β) has a constant value of 1.15. In case of PRC piers having ungrouted tendons, values of (β) should be increased by 10% over those values shown in Fig. 5. In case of RC piers, the two parameters (α) and (β) of the two unloading stiffnesses (K_{r1}) and (K_{r2}) are identical and equal to 0.4.

$$\lambda = \Sigma(Aps_i.Fp_i) / (\Sigma As_i.Fs_i + \Sigma Aps_i.Fp_i) \quad (1)$$

$$M = M_{max.} (1-\lambda) \quad (2)$$

$$K_{r1} = (M_c + M_y) / (\theta_c + \theta_y) \, |\theta_y / \theta_m|^{\alpha} \quad (3)$$

$$K_{r2} = (M_c + M_y) / (\theta_c + \theta_y) \, |\theta_y / \theta_m|^{\beta} \quad (4)$$

where:

Aps_i = Area of each layer of PC tendons
Fp_i = Stress of each layer of PC tendons
As_i = Area of each layer of reinforcing bars
Fs_i = Yielding stress of reinforcing bars
M_c = Cracking moment of the pier
M_y = Yielding moment of the pier
K_{r1} = First unloading Stiffness
K_{r2} = Second unloading Stiffness
θ_c = Cracking rotation of the pier
θ_y = Yielding rotation of the pier
θ_m = Maximum rotation at the current cycle
α,β = Unloading stiffness parameters

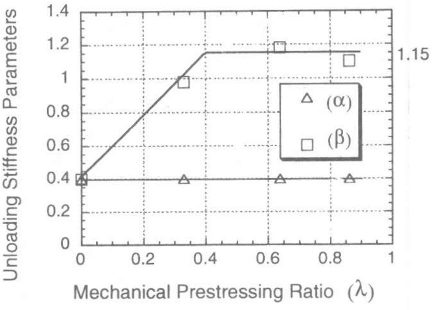

Fig. 5: Relationship between (λ) and unloading stiffness parameters (α,β)

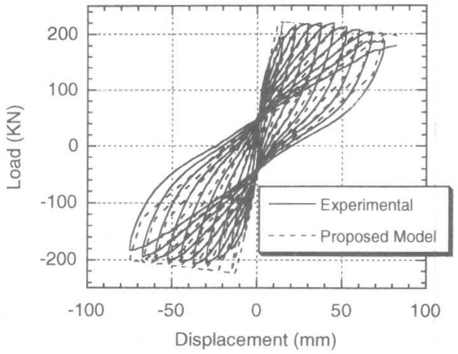

Fig. 6: Load-displacement curve for (S-3)

5. VERIFICATION OF THE PROPOSED RESTORING FORCE MODEL

In order to verify the accuracy of the proposed model for use for PRC piers, experimental results for specimens (S-1) through (S-5) were compared with results obtained by the model. Because of space limitations, results of specimen (S-3) are shown here as an example for the results obtained for PRC piers. Fig. 6 shows the hysteretic load-displacement curve for specimen (S-3). It can be seen that there is a noticeable good accuracy in terms of residual displacement after each cycle as well as the total absorbed energy. A comparison between results obtained using the

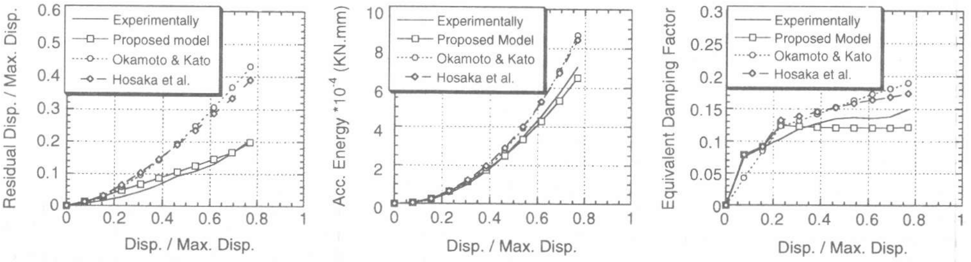

Fig. 7: Characteristics of PRC specimen (S-3)

model by Okamoto et al. (Fig. 1). the model by Hosaka et al. (Fig. 2) and the proposed model (Fig. 6) shows that the proposed model has an advantage over the others in predicting the residual displacement.

Fig. 7 shows a comparison of characteristics of PRC piers between results obtained using the model by Okamoto et al., the model by Hosaka et al. and the proposed model. Fig. 7 implies that a better prediction of residual displacement can be obtained when using the proposed model. Prediction of accumulated absorbed energy and equivalent damping factor are also of a considerable accuracy.

The model examination was extended for cases when PRC were excited by real earthquake [1]. Fig. 8 shows a comparison between displacement-time histories obtained experimentally and using the proposed model for RC specimen (S-1P). There is a good accuracy in terms of the maximum displacement and its associated time as well as the final residual displacement. Based on the obtained good accuracy, the model can be used for RC piers.

Fig. 9 shows the hysteretic load-displacement curve for ungrouted PRC specimen (S-4P). A comparison between results obtained experimentally and using the proposed model showed an overall good accuracy. A considerable accurate prediction of maximum and residual displacements in Fig. 10 of displacement-time histories confirmed the usability of the proposed model.

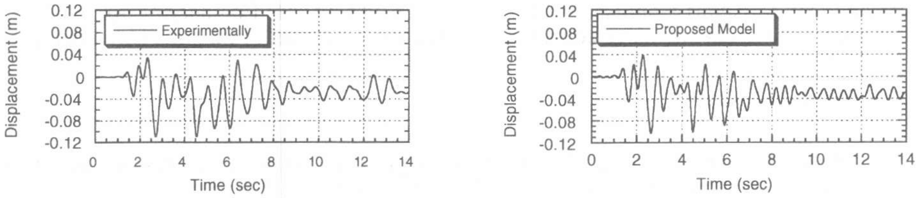

Fig. 8: Displacement-time history for RC specimen (S-1P)

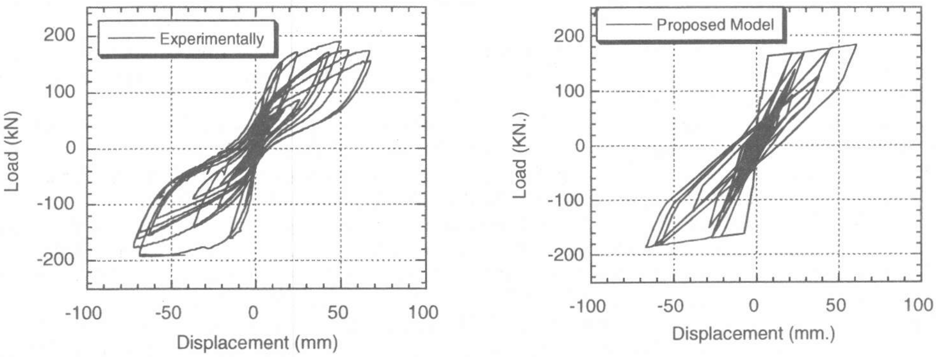

Fig. 9: Hysteretic load-displacement curve for ungrouted specimen (S-4P)

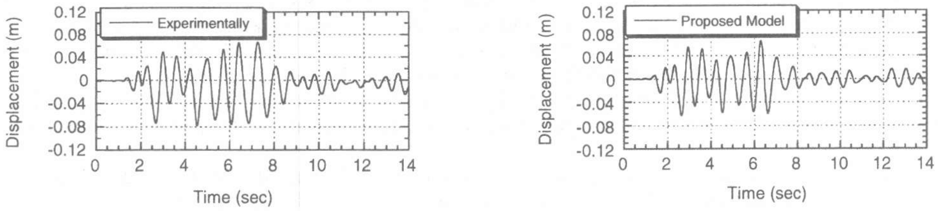

Fig. 10: Displacement-time history for ungrouted specimen (S-4P)

6. CONCLUSIONS

Partially prestressed concrete has shown superior restoration characteristics and small residual displacements that encourage its implementation in actual bridge piers. Results obtained from reversed cyclic loading tests are used to obtain accurate characteristics of those PRC piers. Also, a restoring force model that can capture these characteristics is proposed. To verify the accuracy of the proposed model, a comparison between results obtained using it and those obtained from pseudo dynamic tests is conducted. The comparison showed good agreement in predicting residual displacement, maximum response and overall hysteretic behavior thus allowing for its future implementation in dynamic analyses.

The proposed restoring force model has the following advantages; (1) It has a superior prediction of residual displacements after simulated earthquake excitations. (2) It can cover the whole range of concrete members ranging from fully PC to RC members. (3) It can account for cases when ungrouted PC tendons exist. (4) Changes in amount and arrangement of PC tendons and non-prestressing reinforcement can be taken into consideration. (5) Reasonable estimation of absorbed energy, especially at small displacement amplitudes, can be obtained.

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